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14. ABSTRACT

All project goals have been achieved:
I. Quantum cascade lasers (QCLs) for lambda ~ 4.5 micron operation have been designed, grown, fabricated, and tested.
II. Fabricated QCLs were epi-transferred to the silicon-on-sapphire (SOS) platform using approximately 250-nm-thick SU-8 adhesive layer. QCL-on-SOS devices were fabricated and tested. QCL-to-SOS mode coupler based on tapered waveguide was designed.

15. SUBJECT TERMS

Silicon-on-sapphire, mid-infrared photonics, quantum cascade lasers, printing transfer

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Mikhail Belkin
UU	UU	UU	UU		19b. TELEPHONE NUMBER 512-471-6179

Report Title

Final Report: W911NF-12-R-0012-03: Hybrid Quantum Cascade Lasers on Silicon-on-sapphire

ABSTRACT

All project goals have been achieved:
I. Quantum cascade lasers (QCLs) for lambda ~ 4.5 micron operation have been designed, grown, fabricated, and tested.
II. Fabricated QCLs were epi-transferred to the silicon-on-sapphire (SOS) platform using approximately 250-nm-thick SU-8 adhesive layer. QCL-on-SOS devices were fabricated and tested. QCL-to-SOS mode coupler based on tapered waveguide was designed.
III. Mode-coupled QCL on SOS were fabricated. Room-temperature operation of QCL-on-SOS was successfully demonstrated. Mid-IR light coupling to the SOS waveguide was experimentally confirmed.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

S. Jung, J.H. Kim, Y.Jiang, K. Vijayraghavan, and M.A. Belkin, "Hybrid quantum cascade lasers," 2016 International Quantum Cascade Laser School and Workshop, Cambridge, UK, September 2016.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

2016 – Fellow of the OSA, class of 2016
2015 – Alexander von Humboldt Foundation Wilhelm Bessel Research Award

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Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Seungyong Jung	0.60
FTE Equivalent:	**0.60**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Mikhail A Belkin	0.01	
FTE Equivalent:	**0.01**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

1. List of Appendixes, Illustrations and Tables

2. Statement of the problem studied

Short-wavelength infrared (SWIR, λ~1-3 μm) photonics systems based on silicon-on-insulator (SOI) platforms have undergone a tremendous expansion in recent years, driven initially by applications in fiber-optics communications and optical interconnects and later expanding to beam combining/multiplexing, beam steering, chemical and biological sensing, and frequency comb generation. The development of hybrid III-V diode lasers on the SOI platform has enabled the implementation of fully integrated photonics systems with various functionalities as listed above in which light generation, manipulation, and, if necessary, detection occurs on the same chip.

Mid-infrared (mid-IR) spectral range (3-12 μm), which includes both mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) regions, has recently undergone a dramatic transformation with the development of quantum cascade lasers (QCLs) that can now operate at room temperature in the entire mid-IR range. MWIR and LWIR photonics systems have numerous applications of interest to the Army, including chemical/biological sensing and spectroscopy, free-space communications, power combining, and infrared countermeasures. QCL-based systems have so far been designed around free-space optics. Similar to SWIR PICs, an integration of QCL material with a suitable low-optical-loss wafer-scale platform will enable the development of mid-IR PICs that will provide compact high-reliability on-chip solution for mid-IR applications with an added benefit of possible integration of electronics and photonics circuits on the same chip.

In this project we have developed a process for epitaxial transfer-printing of QCL devices on a silicon-on-sapphire (SOS) platform that provides low-loss optical wave guiding in MWIR. SOS wafers consist of a thin layer of silicon on top of a sapphire substrate. We demonstrate room-temperature operation of QCLs-on-SOS and light coupling from QCL waveguides to SOS waveguides.

3. Summary of the most important results

Quantum cascade lasers (QCLs) for lambda ~ 4.5 micron operation have been designed, grown, fabricated, and tested. The laser structure is given in Table 1.

Layer type	Layer thickness and doping	
	Thickness (nm)	Doping (cm^{-3})
InP substrate	350000	Semi-insulating
InP buffer layer	2000	2.00E+16
InGaAs current injection layer	330	7.00E+17
InP lower outer cladding layer	100	5.00E+16
InGaAs lower inner cladding layer	330	2.00E+16
Active region	1512	1.61E+16
InGaAs upper inner cladding layer	300	2.00E+16
InP upper outer cladding layer 1	2700	2.00E+16
InP upper outer cladding layer 2	150	2.00E+17
InP contact layer	200	5.00E+18

Table 1. The layers sequence of the grown QCL device.

The active region consisted of 30 repetitions of the double resonant phonon depopulation design optimized for emission at 4.5 microns. The wafer was grown, free of charge, by Prof. Dan Botez of the University of Wisconsin – Madison. Ridge-waveguide devices on the native InP substrate were successfully processed and demonstrated pulsed room-temperature operation with threshold current density of approximately 2.5 kA/cm^2. Due to a slight deviation in the QCL layers thickness from target, the actual laser emission wavelength was slightly different from the target (the actual emission wavelength was in 4.6-4.8 microns range, see Fig. 4); however, the difference is not critical for the project goals.

QCL devices, consisting of the laser waveguide and the taper sections (to be described below), were then fabricated on the native InP substrate and epi-transferred to the silicon-on-sapphire (SOS) platform using the adhesive bonding process developed during the course of this project. Lateral current extraction scheme was used in these devices to extract current from below the active region.

The process is shown schematically in Fig. 1. First, the supporting elements made of SU-8 photoresist epoxy were formed next to the QCL ridges to protect them from damage during the bonding process. Then, the processed devices on their native InP wafer were bonded,

episide-down, onto a glass slide using a Crystalbond 509 glue. Following the glass slide bonding, the InP substrate was thinned down to 200 µm by mechanical polishing and then selectively removed using selective wet etching with a 11% hydrochloric acid solution. The InGaAs current injection layer (see Table 1) was used as an etch-stop layer. The exposed surface of the InGaAs current injection layer was brought into contact to the SOS wafer coated with a 250-nm-thick SU-8 epoxy layer and the QCL devices were thermo-compressively bonded to the SOS wafer. The bonding was performed under 1 MPa pressure at 180 degrees C using AML Wafer aligner and bonder system in the UT Austin cleanroom. Under these conditions, the SU-8 epoxy forms a strong bond to SOS wafer and QCL devices. The transfer process was completed by dissolving the Crystalbond 509 glue with acetone and removing the glass slide.
The SOS waveguide pattern was then defined photolithographically over the QCL tapers and the SOS waveguides were defined by dry etching. The images of the tapered QCL devices epi-transferred to SOS are shown in Fig. 2.

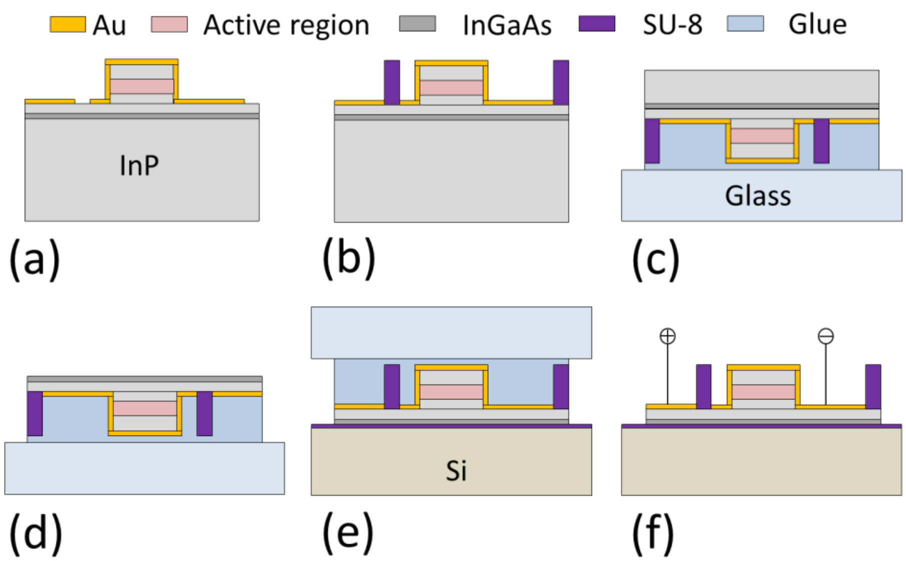

Figure 1. The epi-transfer procedure. (a) A fully-processed QCL on InP. (b) Supporting elements made of SU-8 photoresist epoxy are formed via optical lithography. (c) Devices with the SU-8 supporting elements are bonded on a glass slide with a Crystalbond 509 glue. (d) The InP substrate is removed via selective etching. (e) The QCL is bonded to a Si substrate with the SU-8 epoxy adhesive. (f) The glass slide and the Crystalbond glue is removed by acetone and the class slide is detached from the device.

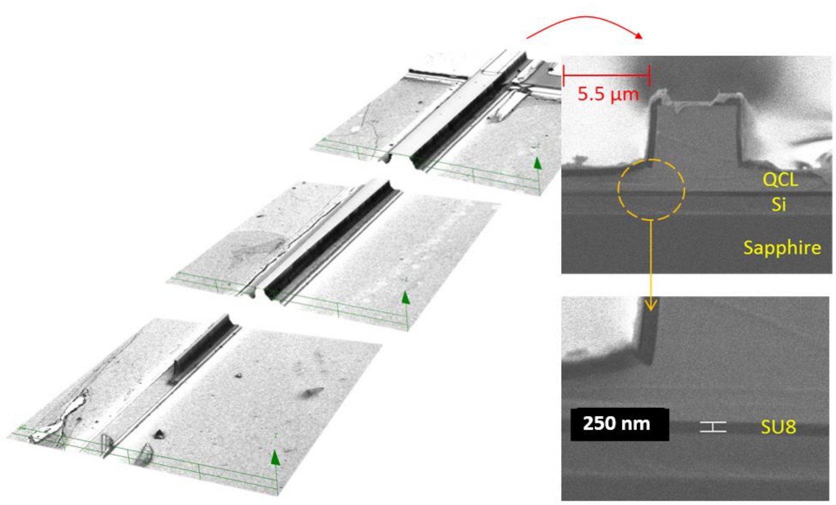

Figure 2. Images of the transferred tapered QCL-on-SOS. (left) The conformal laser microscope images of different sections of the tapered QCL-on-SOS. (top-right) Scanning electron microscope image of the QCL-on-SOS cross section. (bottom-right) Scanning electron microscope image of the SU-8 bonding layer. Bonding layer thickness is 250 nm.

The QCL taper was designed to efficiently couple light from the QCL waveguide to the SOS waveguide. The schematics of the taper is shown in Fig. 3. Figure 4 shows the simulation of the mid-infrared light transfer from the QCL waveguide to the SOS waveguide through the taper. Simulation assumes 1-mm-long taper section length and no waveguide loss. The QCL-to-SOS coupling efficiency is estimated to be approximately 30% for the experimentally-measured SU-8 layer thickness of 250 nm.

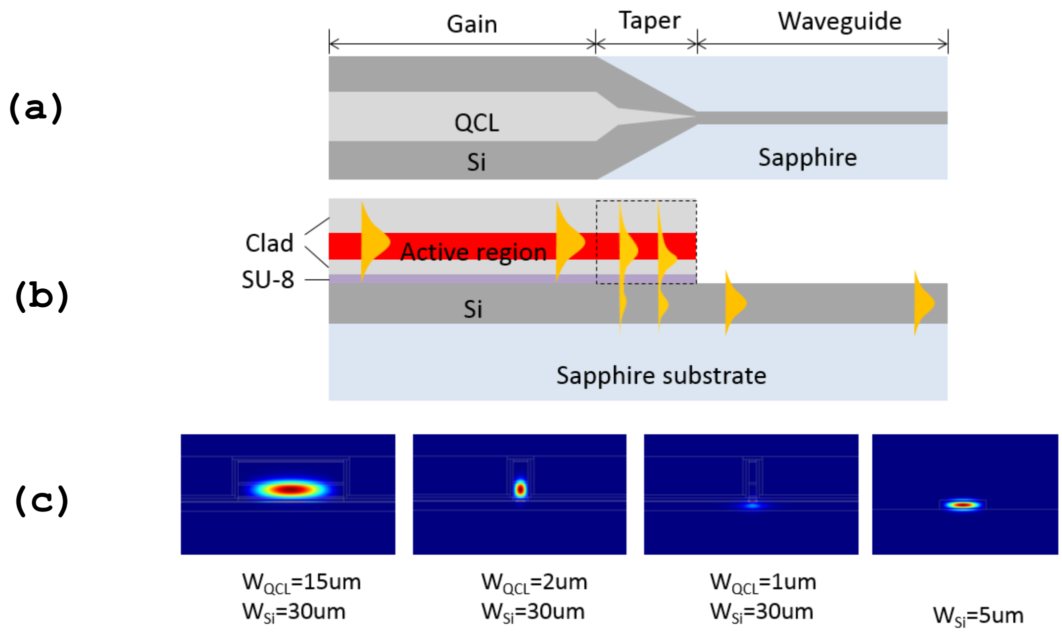

Fig. 3. (a) The top view of the tapered QCL device structure. A 15-μm-wide ridge-waveguide QCL is tapered to couple the fundamental QCL mode into the fundamental mode of a 5-μm-wide 1.2-μm-high Si-on-sapphire (SOS) ridge waveguide. (b) The schematic of the optical mode evolution from the QCL to the SOS waveguide. (c) Simulations of the mode profile at different sections of the waveguide, from left to right: the 15-μm-wide ridge-waveguide QCL section on top of SOS, the 2-μm-wide tapered QCL waveguide on top of SOS, the 1-μm-wide tapered QCL waveguide on top of SOS, the SOS waveguide only. Calculations are performed in COMSOL Multiphysics.

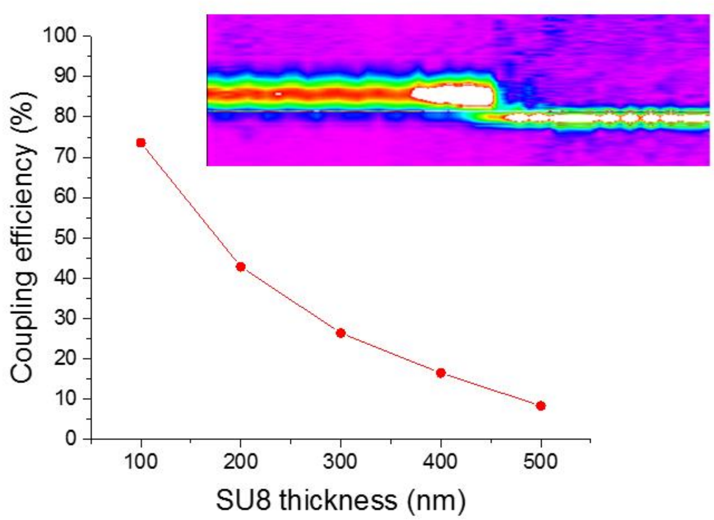

Fig. 4. Simulated efficiency of light coupling from the QCL ridge-waveguide to the SOS ridge waveguide, based on the structure shown in Fig. 3 as a function of SU-8 layer thickness. Inset: simulation of the mid-infrared mode transfer from the QCL ridge-waveguide to the silicon ridge-waveguide through the taper.

Figure 5 shows the emission spectrum and the current-voltage (IV) and light output-current (LI) characteristics of the transferred device. The device consisted of a 2.5-mm-long QCL gain section, a 1-mm-long taper section, and a 3-mm-long Si waveguide section. The light power output was measured from the 3-mm-long Si waveguide section. The device was operated at room temperature with 50 ns current pulses at 2.5 kHz repetition frequency. A piece of liquid crystal thermal absorber was used to block any possible light coming from outside of the SOS waveguide facet as shown in see Fig. 6(a).

We have observed an increase in the threshold current density for a tapered transferred devices (~5.6 kA/cm^2) compared to the 2.5-mm-long ridge-waveguide QCL on a SOS substrate without the taper and Si waveguide sections (~5.3 kA/cm^2), which is attributed to the additional waveguide loss introduced by the passive taper section. Threshold current density of the epi-transferred devices was significantly higher than that of device on InP substrates (2.5-3 kA/cm^2). This may be due to increased thermal resistance of the transferred devices or by stronger-than expected leakage of the laser into the SOS waveguides in the QCL-on-SOS devices. Detailed investigation of the origin of the threshold current density increase go beyond this short 'prof-of-concept' STIR project. We note, however, that the leakage of the laser mode to the SOS waveguide can be addressed by straightforward laser waveguide design adjustment and the increase of the thermal resistance of QCLs-on-SOS may be addressed by operating devices in the episide-down configuration on suitable heat sinks.

Figure 6(b) and 6(c) show the images of the mid-IR emission from a facet of the 3-mm-long SOS waveguide section of our device. The images were taken by a cooled InSb camera. Figure 6(d) and 6(e) show the far-field profiles measured along the lateral (in plane of the SOS substrate) and transverse (perpendicular to the SOS substrate plane) directions, respectively. The data is compared to the simulated far-field profiles obtained from the 2-dimentional mode simulation in BeamProp. The measured profiles follow the overall trend of the simulated profile. Contribution from scattered light at the rough Si facet is most likely responsible for the sharp peak that appears in the lateral profile in Fig. 6(d).

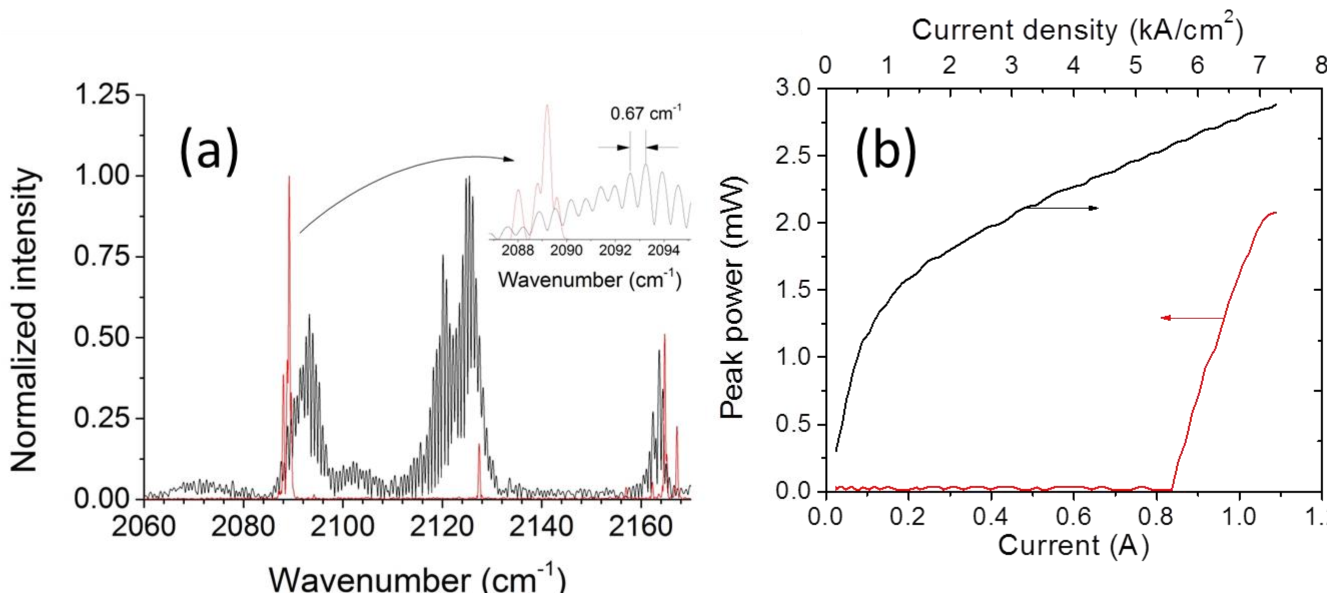

Fig. 5. (a) The room-temperature emission spectrum of the QCL-on-SOS described in the text (red) vs the spectrum of a reference QCL-on-SOS device without the taper and Si waveguide sections (black). (b) IV and LI of the QCL-on-SOS device described in the text. The optical power is collected from the 3-mm-long SOS waveguide section.

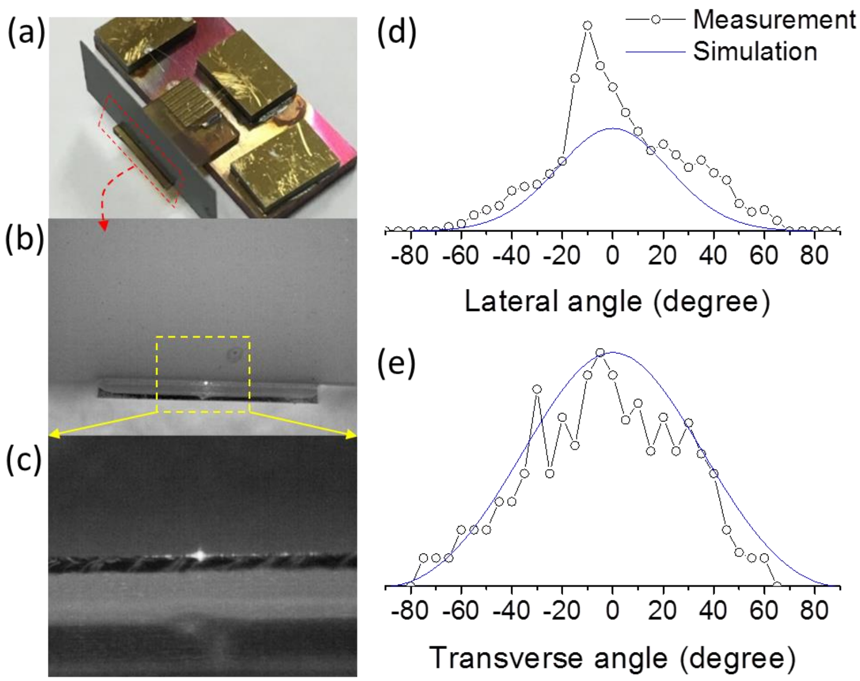

Fig. 6. (a) A photograph of a laser bar with 5 QCL-on-SOS devices mounted on a copper heat sink. The liquid crystal thermal absorber is attached to block mid-IR emission from any sections of the laser structure besides the facet of a 3-mm-long SOS waveguide section. (b,c) Images of the mid-IR emission from a facet of the 3-mm-long SOS waveguide section of our device taken at low (b) and high (c) magnification. The red box in (a) indicates the image orientation. The laser was biased with 900 mA 50-ns current pulses at the repetition frequency of 2.5 kHz. A cooled InSb camera was used to take the images. (d,e) The measured (open-circle) and simulated (solid) far-field profiles of the emission from the facet of a 3-mm-long SOS waveguide section in the lateral (b) and transverse (e) directions.

In summary, all the goals of the STIR project have been achieved: (a) QCLs for lambda ~ 4.5 micron operation have been designed, grown, fabricated, and tested; (b) QCLs were epi-transferred to the SOS platform using an approximately 250-nm-thick SU-8 adhesive layer. QCL-on-SOS devices were fabricated and showed pulsed-mode operation at room-temperature; (c) tapered-waveguide mode-coupled QCL on SOS were fabricated; room-temperature pulsed operation of the tapered QCL-on-SOS was successfully demonstrated and nearly 2 mW of mid-IR power output was recorded from the 3-mm-long SOS waveguide section.

The results of this investigation have been presented in the 2016 Quantum Cascade School and Workshop conference in Cambridge, UK [1]. A paper reporting the results presented in this report is currently being prepared for publication [2].

4. Bibliography

[1] S. Jung, J.H. Kim, Y.Jiang, K. Vijayraghavan, and M.A. Belkin, “Hybrid quantum cascade lasers,” 2016 International Quantum Cascade Laser School and Workshop, Cambridge, UK, September 2016.
[2] S. Jung, J.Kirch, L.J. Mawst, D. Botez, and M.A. Belkin, “Transfer-printed quantum cascade lasers on silicon-on-sapphire platform,” in preparation (2016).

5. Appendixes

None.